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Quantum Statistics and Parton Distributions

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Abstract

A novel approach to parton distributions parameterization in terms of quantum statistical functions is here outlined. The description, already proposed in previous publications, is here improved by adding to the statistical distributions an unpolarized *liquid* component. This new contribution to fermion partons is able to reproduce the expected low x behaviour of structure functions. The analysis provides a satisfactory description of polarized and unpolarized deep inelastic data and shows a possible connection between the Gottfried and Bjorken sum rules.

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1 Introduction

In a recent series of papers [1]-[8] the role of Pauli exclusion principle to explain the experimental data on unpolarized and polarized structure functions of the nucleons has been studied.

The relevance of the quantum statistics on the parton distribution is supported by several phenomenological observations. The most relevant phenomenon is certainly the measurement of a defect in the Gottfried sum rule [9, 10]. It can be explained in terms of a Pauli blocking effect on the production of u sea quark with respect to d sea quark, which yields a flavour asymmetry between \bar{u} and \bar{d} in the proton. Another interesting observation is a relationship which seems to occur between the shapes of the quark parton distributions and their first momenta, which is the typical characteristic of Fermi–Dirac distribution functions.

These considerations naturally suggest to use quantum statistically inspired parameterizations for the parton distribution functions. In this description, the independent variable which plays the role of the energy is the Bjorken variable x , and the distributions assumed will be of the Fermi–Dirac kind for quarks, and Bose–Einstein for gluons. Interestingly, to properly describe the low x behaviour of the structure functions, a *liquid* unpolarized component dominating the very low x region has to be added. It does not affect the quark parton model sum rules (QPMSR) but it is necessary to reproduce the antiquark distribution at low x .

The paper is organized as follow, in Section 2 we summarize the phenomenological motivations behind our description for the parton distributions. In Section 3 the distribution function parameterizations are shown in detail and discussed in connection with a possible physical interpretation. Section 4 deals with the results of a fitting procedure performed to get the free parameters of the distribution functions. The theoretical predictions are shown in comparison with the experimental data and the results for QPMSR are also discussed. In Section 5 we give our conclusions and remarks.

2 Evidence for quantum statistical effects in parton distributions

As already stated, an experimental evidence for a central role played by the Pauli principle in the physics of nucleon is the defect in the Gottfried sum rule [9]

$$I_G = \int_0^1 \frac{1}{x} [F_2^p(x) - F_2^n(x)] dx = \frac{1}{3}(u + \bar{u} - d - \bar{d}) , \quad (1)$$

that for $SU(2)_I$ invariant sea quark distributions ($\bar{d} = \bar{u}$) gives $I_G = 1/3$. Indeed NMC experiment [10] measures for the l.h.s. of Eq. (1)

$$I_G = 0.235 \pm 0.026 , \quad (2)$$

implying

$$\bar{d} - \bar{u} = 0.15 \pm 0.04 \quad u - d = 0.85 \pm 0.04 . \quad (3)$$

This experimental result can be explained following the idea of Field and Feynman [11], who suggested that, in the proton, the Pauli principle depresses the production of $u\bar{u}$ pairs in the proton with respect to $d\bar{d}$, since it contains two valence u quarks and only one d . We will return on this fact in the following to focus on a possible connection between the violation of the above sum rule and the Bjorken one [12].

From the previous considerations one expects a relevant role played by the statistics in the whole phenomenology of deep inelastic scattering, and thus it suggests to look for others typical characteristics of this behaviour.

A peculiar characteristic of a Fermi–Dirac statistical function is certainly the strong connection between shape and abundance. This is an immediate consequence of the Pauli exclusion principle which forbids two or more fermions to have the same quantum numbers and implies that the more abundant is distribution the broader is in x the associated function.

With the aim to check if this situation occurs in the nucleon structure let us consider the abundances of valence quarks in the nucleons. As it is well-known, at $Q^2 = 0$ they are connected to the axial couplings of the baryon octet F and D , through the relations

$$u_{val}^\uparrow = 1 + F \quad u_{val}^\downarrow = 1 - F , \quad (4)$$

$$d_{val}^\uparrow = \frac{1 + F - D}{2} \quad d_{val}^\downarrow = \frac{1 - F + D}{2} . \quad (5)$$

By using the experimental values obtained by the two bodies strong decays of hyperons $F = 0.464 \pm 0.009$ $D = 0.793 \pm 0.009$ [13], [14], we get

$$u_{val}^{\uparrow} \simeq \frac{3}{2} \simeq u_{val}^{\downarrow} + d_{val}^{\uparrow} + d_{val}^{\downarrow} \quad , \quad (6)$$

which tells us that u_{val}^{\uparrow} is the most abundant parton in the proton, at least at $Q^2 = 0$.

Moreover, by observing that $F \simeq 1/2$ and $D \simeq 3/4$ one also gets

$$u_{val}^{\downarrow} \simeq \frac{1}{2} = \frac{d_{val}^{\uparrow} + d_{val}^{\downarrow}}{2} \quad . \quad (7)$$

In addition to this, the behaviour at high x of $F_2^n(x)/F_2^p(x)$ [15], known since a long time, and the more recent polarization experiments [16], [17], which show that at high x the partons have spin parallel to the one of the proton, imply that $u^{\uparrow}(x)$ is the dominating parton distribution in the proton at high x . Thus, to the most abundant u^{\uparrow} corresponds effectively a broader distribution in the Bjorken variable x .

Eq. (7) has also another interesting implication. In a previous work we assumed that the parton distributions at a given large Q^2 depend on their first momenta (abundances) computed at $Q^2 = 0$ [2]

$$p(x) = \mathcal{F}(x, p_{val}) \quad , \quad (8)$$

with \mathcal{F} an increasing function of p_{val} and with a broader shape for higher values of p_{val} .

From this assumption and by virtue of (7) we get

$$u^{\downarrow}(x) = \frac{1}{2} [d^{\uparrow}(x) + d^{\downarrow}(x)] = \frac{1}{2} d(x) \quad , \quad (9)$$

which implies

$$\Delta u(x) = u^{\uparrow}(x) - u^{\downarrow}(x) = u(x) - d(x) \quad . \quad (10)$$

Note that, Eq. (10) connects the contribution of $\Delta u(x)$ to $g_1^p(x)$, with the terms due to up and down quarks in the unpolarized structure functions of nucleons $F_2(x)$ [2]

$$x g_1^p(x) \Big|_{\Delta u} = \frac{2}{3} [F_2^p(x) - F_2^n(x)]_{u+d} \quad . \quad (11)$$

This relation should hold in good approximation for the total quantities $x g_1^p(x)$ and $F_2^p(x) - F_2^n(x)$, since the contribution in $g_1^p(x)$ due to $\Delta d(x)$ is depressed for the twofold reason that $e_d^2 = (1/4)e_u^2$ and $\Delta d_{val} \simeq -(1/4)\Delta u_{val}$. By integrating Eq. (11) one thus get a connection between the spin sum rule and the Gottfried sum rule and in turn a relation between their possible defects.

3 Parton distributions as Fermi–Dirac and Bose–Einstein statistical functions

The previous considerations on the role played by the Pauli principle in the nucleon structure suggest to assume Fermi–Dirac distributions in the variable x , at least for large x , for the quark partons [5]

$$p_\lambda(x) = f(x) \left[\exp\left(\frac{x - \tilde{x}(\lambda)}{\bar{x}}\right) + 1 \right]^{-1}, \quad (12)$$

where the index λ denotes the different species of quarks, characterized by flavour and polarization. In Eq. (12), $f(x)$ is a weight function which accounts for the energy level density, and because it is connected to the nonperturbative aspect of QCD results independent of flavours and polarization. The *universal* parameter \bar{x} represents the *temperature* for the system, whereas $\tilde{x}(\lambda)$ stands the *thermodynamical potential* of the parton λ .

The expression chosen for $f(x)$ is inspired by the expected power behaviour at $x = 0$, and by the obvious kinematical cut which forces the function to vanish at $x = 1$. In order to satisfy these constraints we assume for simplicity a power low dependence on x

$$f(x) = A x^\alpha (1-x)^\beta. \quad (13)$$

Indeed, the assumption that the form given in Eq. (12) for the quark distribution functions, which requires different thermodynamical potentials in order to describe the experimental data, is valid in the low x limit as well has at least two unpleasant features. Firstly, one gets in the nonperturbative region different behaviour for the different parton distributions, where on the contrary one would expect an *universal* dependence on x . Moreover, the power dependence on x of Eq. (13), fitted by the experimental data mostly placed at the large x , is not suitable to reproduce the more divergent contribution expected at low x . This most divergent part does not contribute to QPMSR as the ones given by Gottfried and Bjorken [12] with $I = 1$ quantum numbers exchanged. To this aim we add to (12) an unpolarized component, which we call *liquid* to stress the possibility that it is connected to the presence, at low x , of a new phase in the quark-gluon plasma due to the highly nonperturbative QCD regime

$$p_\lambda(x) = \frac{A_L}{2} x^{\alpha_L} (1-x)^{\beta_L} + A x^\alpha (1-x)^\beta \left[\exp\left(\frac{x - \tilde{x}(\lambda)}{\bar{x}}\right) + 1 \right]^{-1}. \quad (14)$$

In the fitting procedure we take as free parameters, apart from the constants involved in $f(x)$ and in the *liquid* component of (14), the temperature \bar{x} and the \tilde{x} for $u^{\uparrow(\downarrow)}$, $d^{\uparrow(\downarrow)}$, \bar{u} and \bar{d} (the latters are assumed not polarized). We tried initially to introduce spin-dependent \tilde{x} 's also for the \bar{q} 's and to test the relationship

$$\Delta\bar{u}(x) = \bar{u}(x) - \bar{d}(x) \quad , \quad (15)$$

assumed in previous works [2, 6], but unfortunately, we found practically the same χ^2 with negative and positive values for $\Delta\bar{u}(x)$ and/or $\Delta\bar{d}(x)$. Hence, for not loosing predictivity in the fit procedure we have assumed unpolarized antiquarks.

As far as the strange quarks are concerned, we assume for simplicity unpolarized distribution functions given by the empirical expression

$$s = \bar{s} = \frac{\bar{u} + \bar{d}}{4} \quad , \quad (16)$$

which experimentally is very well satisfied.

Analogously, for the gluons, if we neglect their polarization, the bosonic statistic suggests the consider, at large x , the distribution function

$$G(x) = \frac{16}{3} A x^\alpha (1-x)^\beta \left[\exp\left(\frac{x - \tilde{x}_G}{\bar{x}}\right) - 1 \right]^{-1} \quad , \quad (17)$$

where the factor $16/3$ is just the product of 2 ($S_z(G) = \pm 1$) times $8/3$, the ratio of the colour degeneracies for gluons and quarks.

4 Discussion of the results

By assuming for the parton distributions Eqs. (14) and (17), we fit the distribution parameters from the experimental data for $F_2^p(x) - F_2^n(x)$ [10], $xF_3(x)$ [18], $xg_1^p(x)$ [16, 17] and $xg_1^n(x)$ [19], which do not receive contributions from the *liquid* component, and from $F_2^n(x)/F_2^p(x)$ [10] and $x\bar{q}(x)$ [20].

The available experimental data on deep inelastic scattering observables correspond in general to different values of Q^2 . This would suggest, in order to use the data to determine the distribution parameters, which in general will depend on Q^2 , to apply the evolution equations to lead all the experimental results to the same Q^2 . In our analysis we have neglected this Q^2 dependence of the distribution parameters, since we expect

from the evolution equations a smooth logarithmic dependence. As far as the polarized distributions is concerned, in fact, the expected Q^2 dependance [6] results to be smaller than the experimental errors, and thus our analysis is slightly affected by neglecting this dependance.

Indeed, the data on unpolarized nucleons structure functions are at $Q^2 = 4 \text{ GeV}^2$ [10], the neutrino data at $Q^2 = 3 \text{ GeV}^2$ [18], and \bar{q} measures are performed at $Q^2 = 3 \text{ GeV}^2$ and 5 GeV^2 [20] and differ at small x , while our curve is intermediate between the two sets of data. The data on $g_1^n(x)$ are at $Q^2 = 2 \text{ GeV}^2$ [19], whereas $g_1^p(x)$ is measured at $Q^2 = 10 \text{ GeV}^2$ by SMC [16] and at $Q^2 = 3 \text{ GeV}^2$ by E143 [17]; despite some narrowing of the distribution at higher Q^2 showing up in the data, the values of I_p are in good agreement.

In Table 1 we report the parameters found in the present analysis [8] and compare them with the results of a previous fit (without liquid) [5], and with the ones by Bourrely and Soffer [6] found on similar principles, but with several different assumptions. In the Figures 1.-6., the predictions for the nucleon structure $F_2^p(x) - F_2^n(x)$, $F_2^n(x)/F_2^p(x)$, $xg_1^p(x)$, $xg_1^n(x)$, $xF_3(x)$ and $x\bar{q}(x)$ are shown, respectively, and compared with the experimental data.

The parton distributions found in [8] are described in Figure 7. Since the total momentum carried by fermion partons is 53%, we get $\tilde{x}_G = -1/15$ by requiring that the gluons carry out the remaining part of the proton momentum. In Ref. [8], the gluon distribution is compared with the information found on them in CDHSW [21], SLAC+BCDMS [22] and in NMC [23] experiments at $Q^2 = 20 \text{ GeV}^2$. The agreement is fair for $x > .1$, while the fast increase at small x , confirmed also from the data at very small x at Hera [24], confirms that a liquid component is needed also for gluons. The excess at high x of our curve with respect to experiment may be, at least in part, explained by the expected narrowing of the distribution from $Q^2 = 4 \text{ GeV}^2$, where we fit the unpolarized distributions, to $Q^2 = 20 \text{ GeV}^2$.

The inclusion of the *liquid* term and the extension of our fit to the precise experimental results on neutrinos has brought to substantial changes in the parameters [8] with respect to the previous work [5].

The low x behaviour of $f(x)$ become smoother ($\simeq x^{-.203\pm.013}$ instead of $x^{-0.85}$), but this

is easily understood since the previous behaviour was a compromise between the smooth *gas* component and the rapidly changing *liquid* one to reproduce the behaviour of $\bar{q}(x)$. The *liquid* component, relevant only at small x , carries only .6% of parton momentum and its behaviour $\sim x^{-1.19}$, similar to the result found in [25], is less singular than the one, suggested in the framework of the multipherial approach to deep-inelastic scattering, proportional to $\sim x^{-1.5}$ [26]. The parameter $\tilde{x}(u^\dagger)$ took the highest value allowed by us (1.), since the factor in $f(x)$, $(1-x)^{2.34}$, is taking care to decrease $u^\dagger(x)$ at high x . The temperature \bar{x} is larger than the previous one and the one found by Bourrely and Soffer [6]. Instead $\tilde{x}(u^\dagger)$ is slightly smaller than the previous determination [5] and about half the value found in [6], where $f(x)$ is different for u^\dagger and u^\perp .

The ratio $r = u^\dagger(x)/d(x)$ varies in the narrow range (.546, .564) in fair agreement with the constant value $1 - F = .536 \pm .009$ assumed in [5] and slightly larger than the value $1/2$ taken in [2] and [6].

The central value found for the first moment of $\bar{u}_{\text{gas}}(x)$, .03, is smaller than $\bar{d}_{\text{gas}}(x)/2$, .08, while Eq. (15) implies $\bar{u}(x) \geq \bar{d}(x)/2$. However, the large upper error on \bar{u}_{gas} and the uncertainty in disentangling the gas and liquid contributions for the \bar{q} 's do not allow to reach a definite conclusion about the validity of Eq. (15).

Finally, we can compare the predictions of [8] with the measured asymmetry for Drell-Yan production of muons at $y = 0$ in pp and pn reactions

$$A_{DY} = \frac{d\sigma_{pp}/dy - d\sigma_{pn}/dy}{d\sigma_{pp}/dy + d\sigma_{pn}/dy} , \quad (18)$$

which at rapidity $y = 0$ reads

$$A_{DY} = \frac{(\lambda_s(x) - 1)(4\lambda(x) - 1) + (\lambda(x) - 1)(4\lambda_s(x) - 1)}{(\lambda_s(x) + 1)(4\lambda(x) + 1) + (\lambda(x) + 1)(4\lambda_s(x) + 1)} , \quad (19)$$

where $\lambda_s(x) = \bar{u}(x)/\bar{d}(x)$ and $\lambda(x) = u(x)/d(x)$. At $x = .18$ we have $\lambda_s(.18) = .454$ and $\lambda(.18) = 1.748$ giving rise to $A_{DY}(.18) = -.138$ in fair agreement with the experimental result $-.09 \pm .02 \pm .025$ [27].

The behaviour of $A_{DY}(x)$ is plotted in Figure 8 together with the experimental point measured by NA51 collaboration.

5 Conclusions

We compared with data the quark-parton distributions given by the sum of Fermi–Dirac functions and of a term not contributing to the QPMSR relevant at small x . We obtain a fair description for the unpolarized and polarized structure functions of the nucleons as well as for the $F_3(x)$ precisely measured in (anti)neutrino induced deep-inelastic reactions and for \bar{q} total distribution. The conjectures of previous works on d distributions are well confirmed by the values chosen for their thermodynamical potentials. As long as the implications for QPMSR the values found for the first momenta of the various parton species give l.h.s.’s consistent with experiment. For the fundamental issue of the Bjorken sum rule, as advocated in previous works [1, 4] and [5], we get

$$\Delta u \simeq u - d + 2F - 1 , \quad (20)$$

$$\Delta d \geq F - D , \quad (21)$$

to confirm the suspicion of a violation of Bjorken sum rule related to the defect in the Gottfried sum rule.

A word of caution is welcome for our conclusions on the violation of Bj sum rule, since we did not include the effect of QCD corrections in relating the quark parton distributions to the structure functions. Also we assumed no polarization for \bar{q} , being unable to get a reliable evaluation of $\Delta\bar{q}$ with the present precision for the polarized structure functions at small x . Indeed our description of $g_1^p(x)$ and $g_1^n(x)$ is good in terms of $\Delta u(x)$ and $\Delta d(x)$, but our prediction is smaller than the central values of the three lowest x values measured by SMC.

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Parameters	Previous fit [5]	Fit BS [6]	Actual fit [8] $\chi^2/N = 2.47$	
A	.58		2.66 $^{+.09}_{-.08}$	
α	−.85	−.646 for u_{val}^\uparrow −.262 for u_{val}^\downarrow	−.203 $\pm .013$	
β			2.34 $^{+.05}_{-.06}$	
A_L			.0895 $^{+.0107}_{-.0084}$	
α_L			−1.19 $\pm .02$	
β_L			7.66 $^{+.182}_{-.159}$	
\bar{x}	.132	.092	.235 $\pm .009$	gas abund.
$\tilde{x}(u^\uparrow)$	.524	.510 for u_{val}^\uparrow	1.00 $\pm .07$	1.15 $\pm .01$
$\tilde{x}(u^\downarrow)$	.143	.231 for u_{val}^\downarrow	.123 $\pm .012$	.53 $\pm .01$
$\tilde{x}(d^\uparrow)$			−.068 $^{+.021}_{-.024}$	.33 $\pm .03$
$\tilde{x}(d^\downarrow)$			.200 $^{+.013}_{-.014}$	.62 $\pm .01$
$\tilde{x}(\bar{u}^\uparrow)$	−.216		−.886 $\pm .266$	.015 $^{+.034}_{-.009}$
$\tilde{x}(\bar{u}^\downarrow)$	−.141		''	''
$\tilde{x}(\bar{d}^\uparrow) = \tilde{x}(\bar{d}^\downarrow)$	''		−.460 $^{+.047}_{-.064}$	.08 $^{+.03}_{-.02}$

Table 1. Comparison of the values for the parameters of our best fit [8] with the corresponding quantities, if any, found in previous analysis [5], [6].

Sum rule	Experimental data	Our fit [8]	QPM
GLS	$2.50 \pm .018 \pm .078$ [18]	2.44 $^{+.04}_{-.07}$	3
G	.235 $\pm .026$ [10]	.20 $\pm .02$	1/3
EJ	$\begin{cases} I_p \\ I_n \end{cases}$ $.136 \pm .011 \pm .011$ [16] $.129 \pm .004 \pm .009$ [17]	$.122 \pm .007$ $-.030 \pm .010$	$.188 \pm .005$ $-.021 \pm .005$
Bj	−.022 $\pm .011$ [19]	.152 $\pm .010$	.209

Table 2. Comparison of our predictions for the sum rules with the experimental values and with the quark parton model (QPM) predictions without QCD corrections.

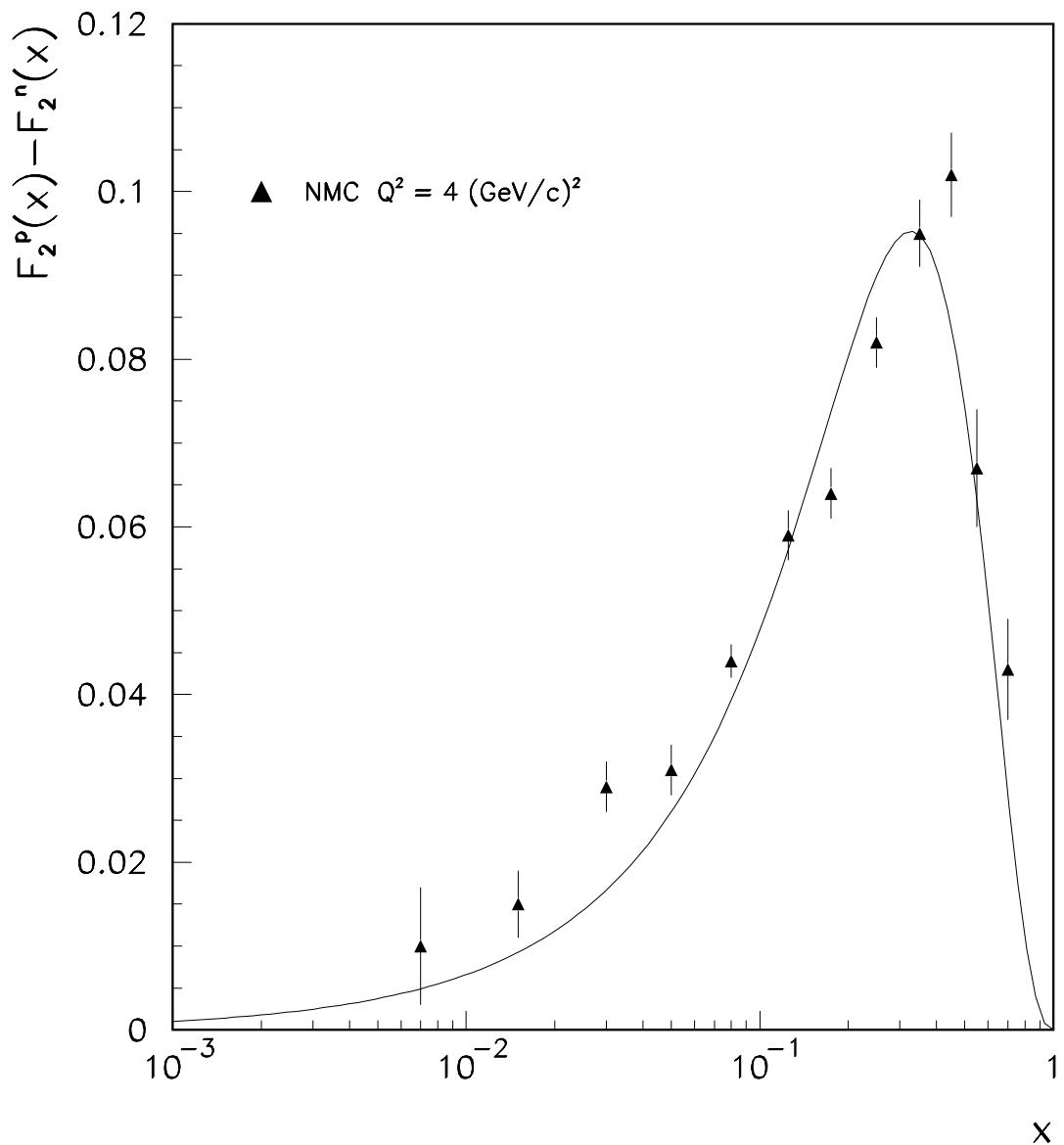


Figure 1: The prediction for $F_2^p(x) - F_2^n(x)$ is plotted and compared with the experimental data [10]

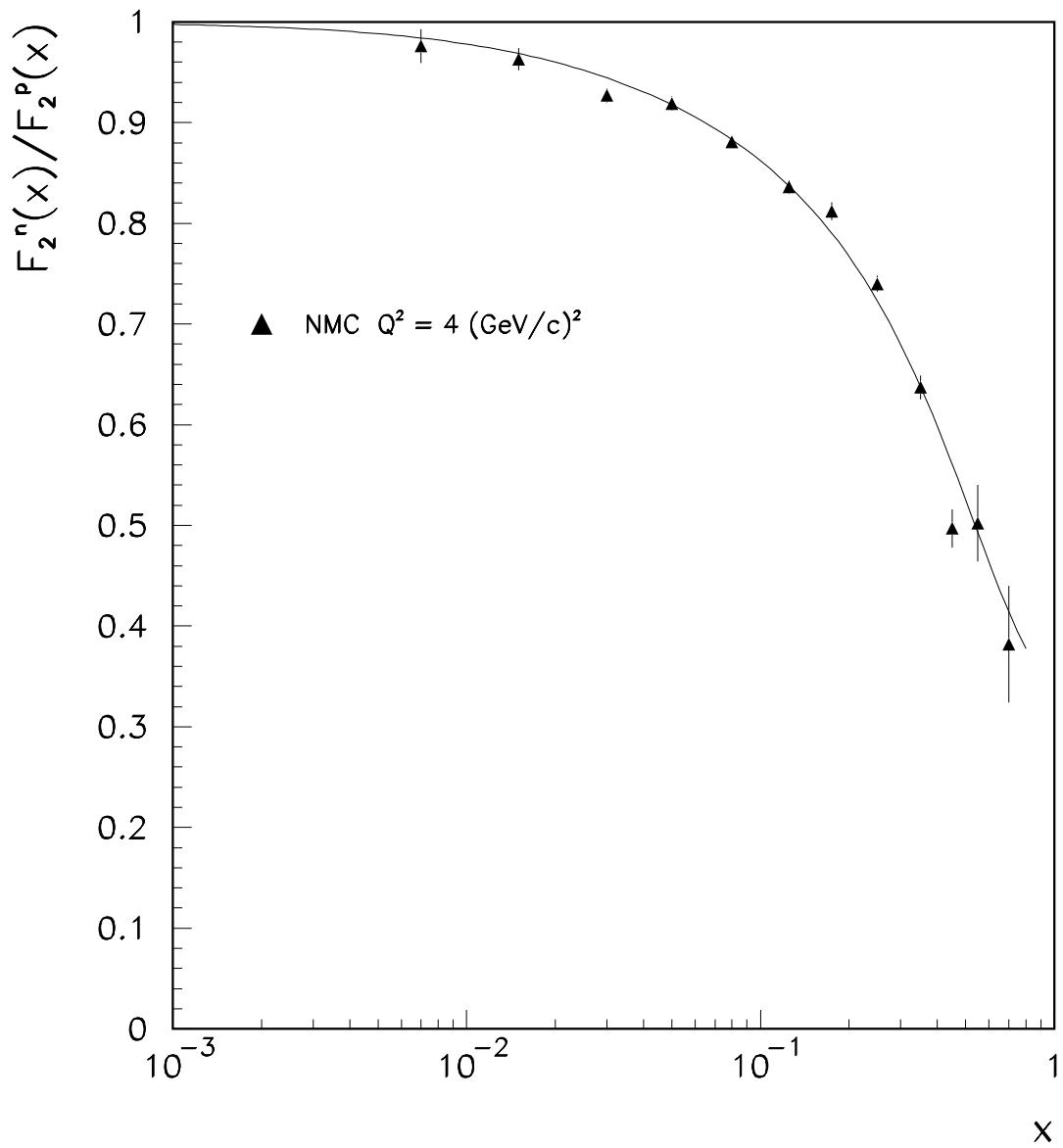


Figure 2: The prediction for $F_2^n(x)/F_2^p(x)$ is plotted and compared with the experimental data [10].

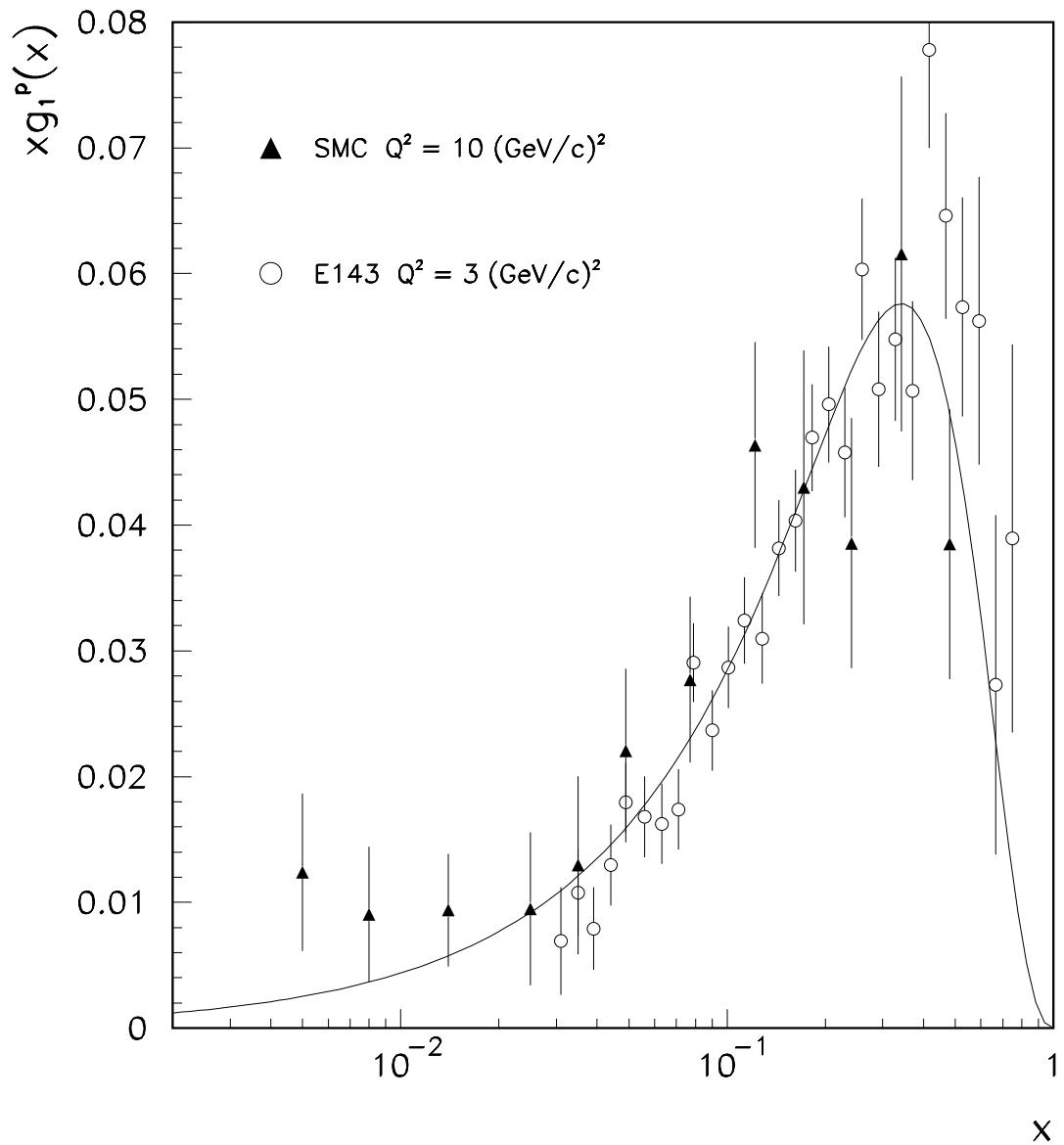


Figure 3: $xg_1^p(x)$ is plotted and compared with the data [18], [19].

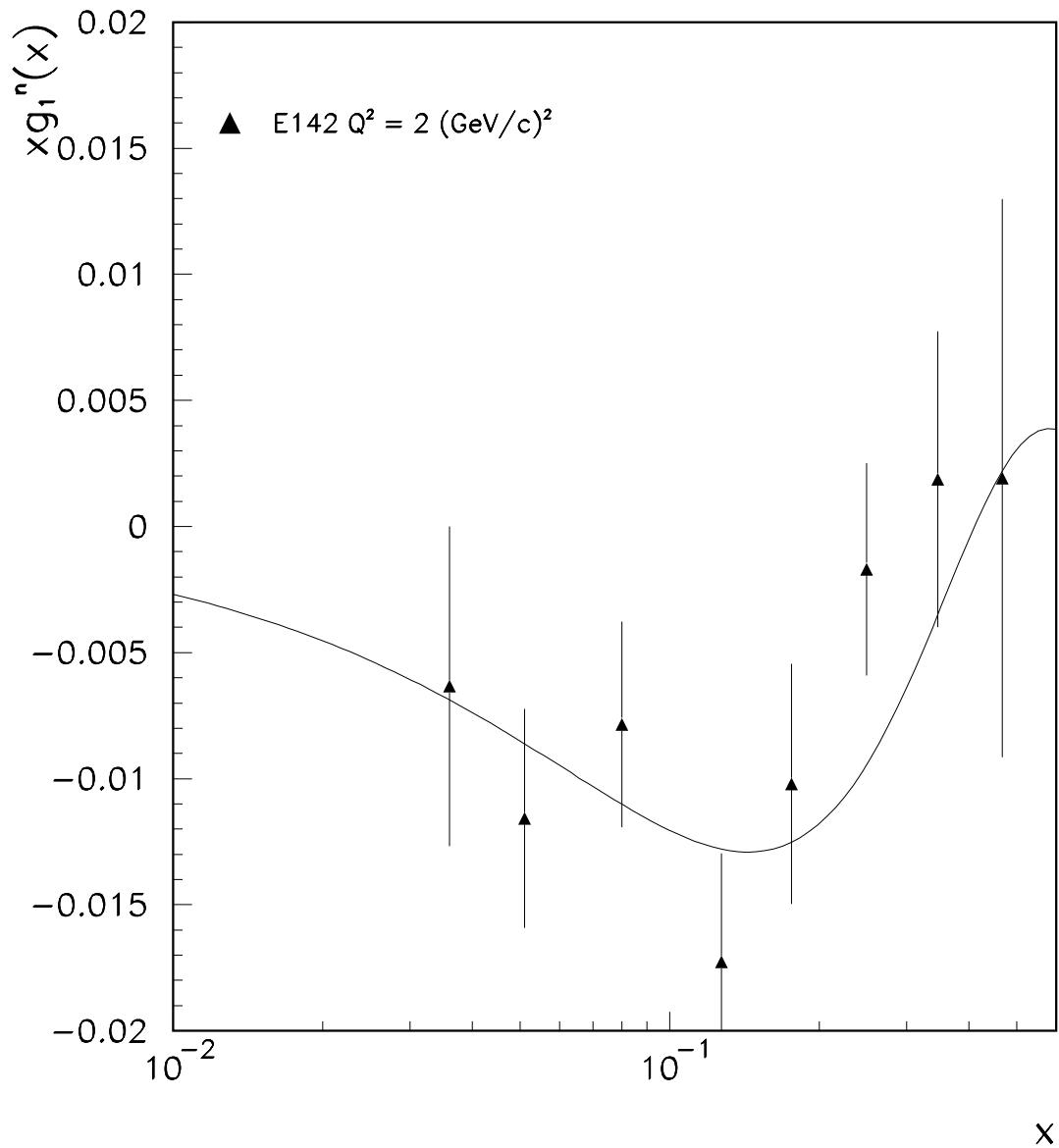


Figure 4: $xg_1^n(x)$ is plotted and compared with the data [21].

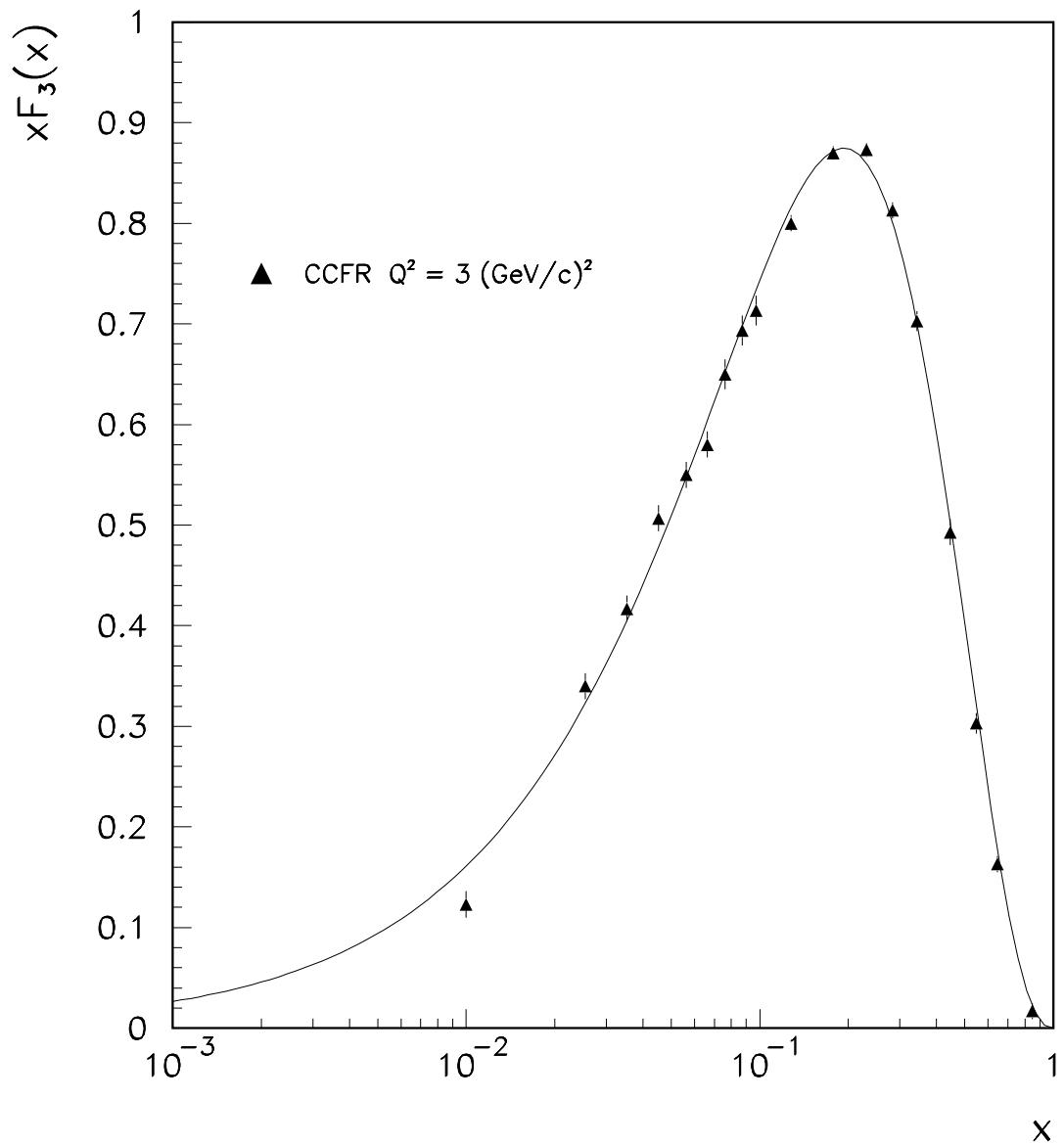


Figure 5: $x F_3(x)$ is plotted and the experimental values are taken from [20].

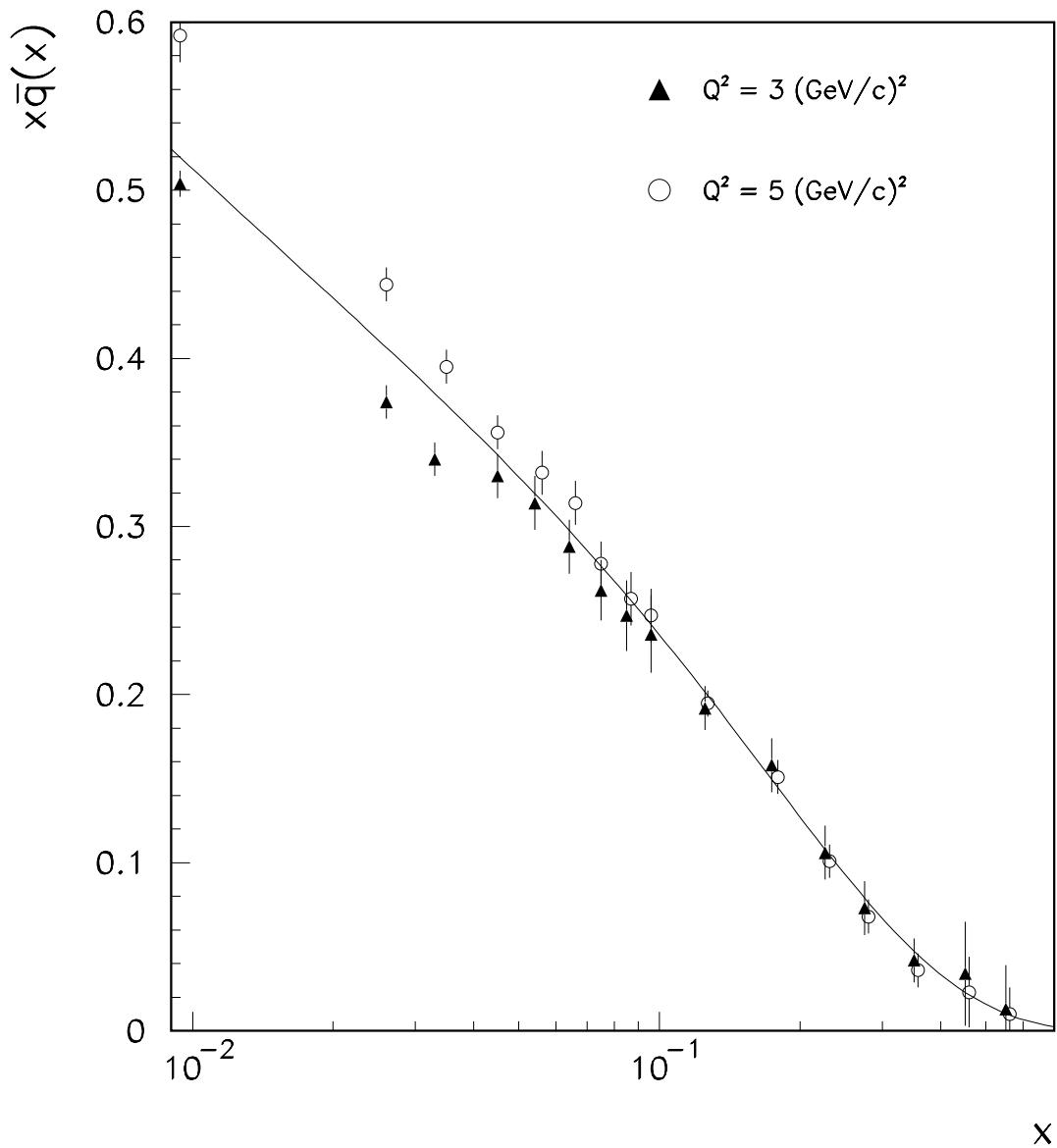


Figure 6: $x\bar{q}(x)$ versus x is shown, the experimental data correspond to [22].

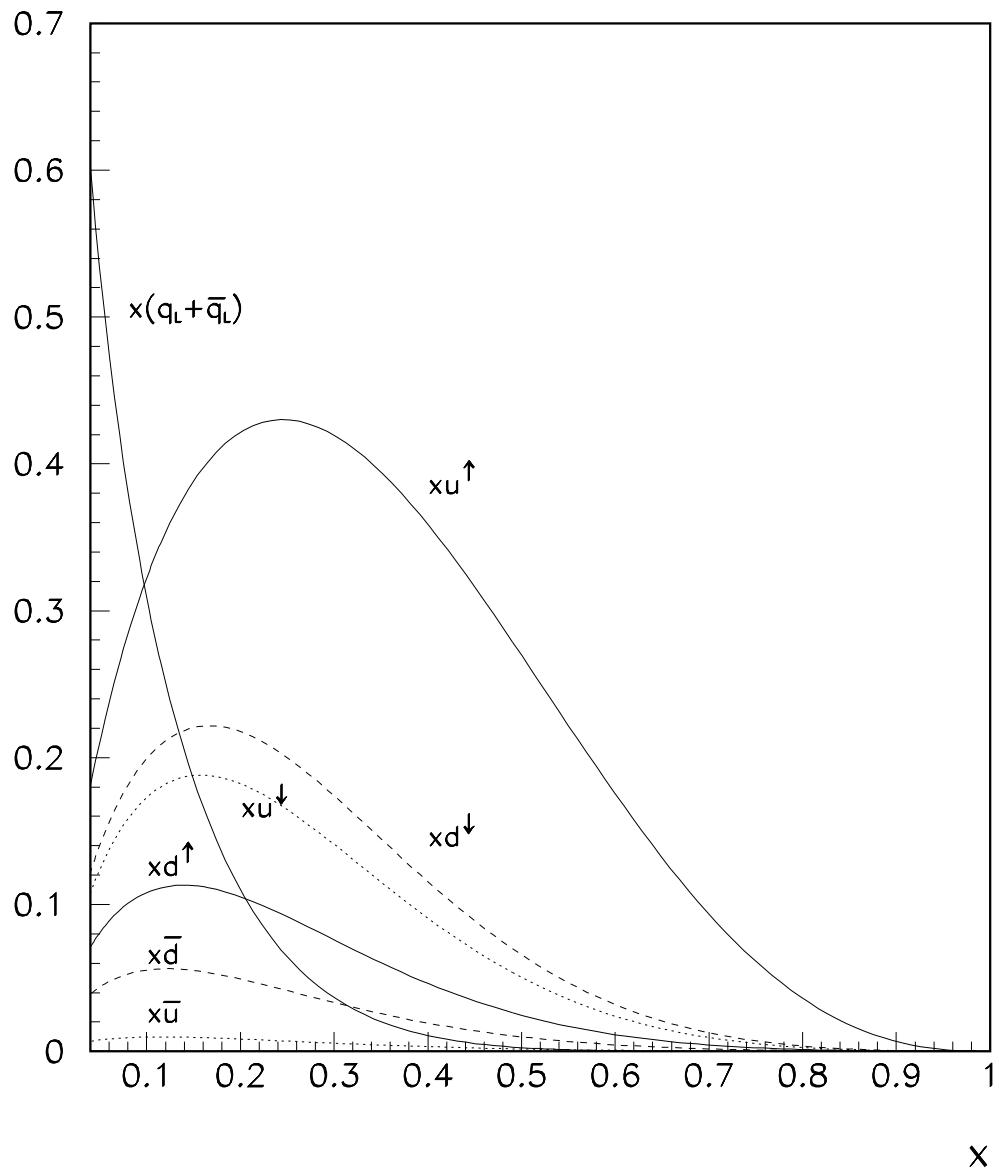


Figure 7: The momentum distributions of *gas* component of q and \bar{q} 's, and of the total *liquid* part are here shown.

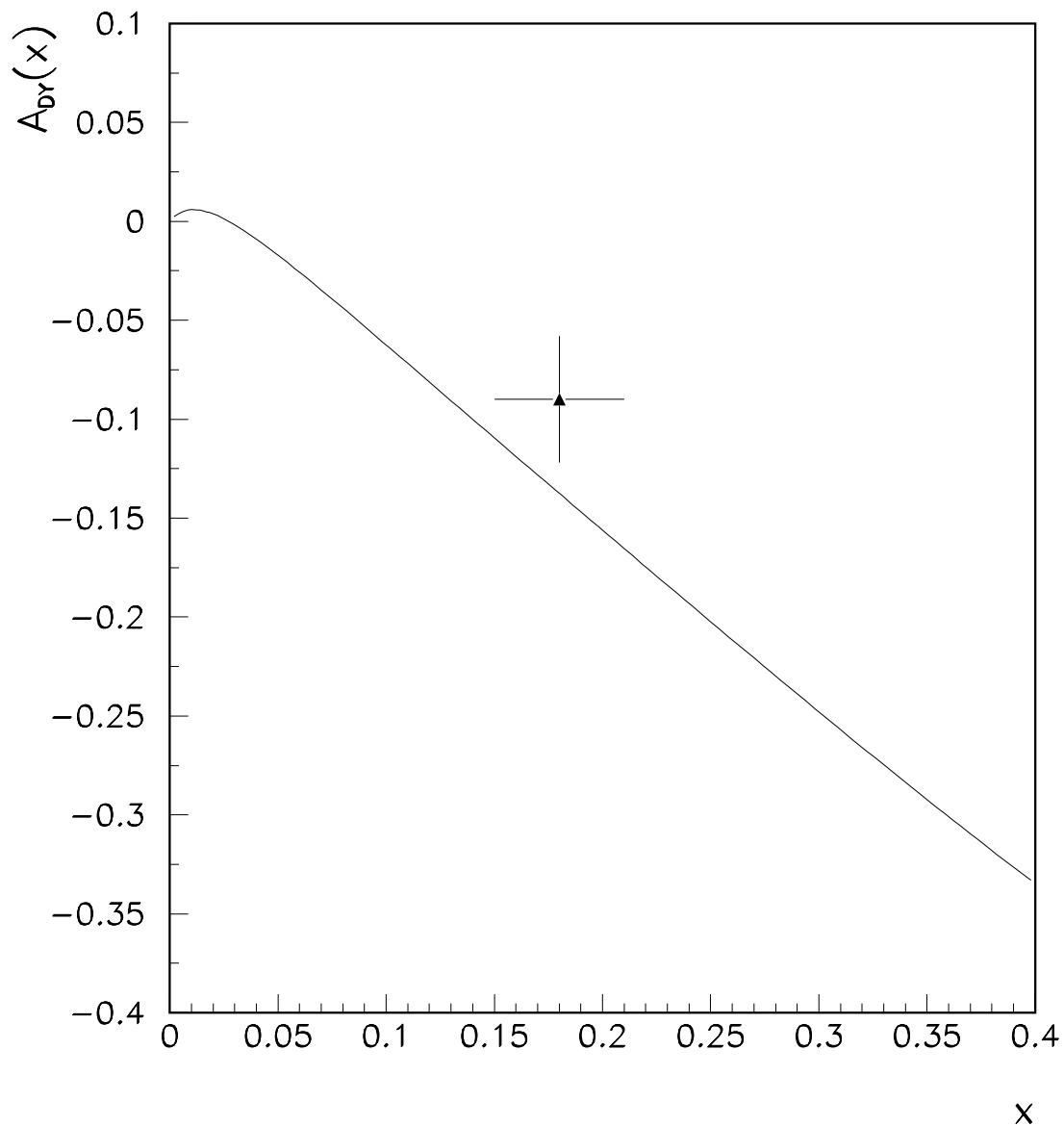


Figure 8: The asymmetry $A_{DY}(x)$ is here plotted, the experimental result is taken from [29].